STUDY OF LOW TEMPERATURE COMBUSTION ENGINE COMBINED WITH HIGH TEMPERATURE FUEL CELL

A

Synopsis

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1. Introduction

All are aware that fossil fuels are depleting rapidly as their consumption and demand around the world is increasing due to uncounted number of vehicles in the world. These vehicles are running on fuels like gasoline, diesel etc. for their energy production which produce lot of engine emissions containing CO, CO_2, HC, SOx, NOx, particulate matter and smoke. These emissions pollute the environment and causing adverse effects on life cycle of living organisms by creating problems like air pollution, smog, global warming etc. [1].

Many countries, governments and organizations around the world are concerned about the pollution created by the Internal Combustion Engines and are focusing on reducing engine emissions greatly by imposing some rules and regulations from time to time, particularly on automotive industries to increase the quality of fuel, using alternate fuel, improve engine quality and combustion techniques. Some of the regulations in this regard are BS IV, BS V, BS VI, EURO V, EURO VI etc. which are quantifying the quantity of emissions produced by engines in parts per million (PPM).

The above scenario necessitates the development of new technology with alternate fuel. Some hybrid systems are needed to developed which may reduce the fuel consumption, engine emission and increase the power output.

Now-a-days many research institutes and industries are focusing on developing new types of automotive that are using technology different from that used in conventional internal combustion engines. One such example is electric vehicles (EVs) which were introduced in 1990s. Now these EVs are growing rapidly in real world and governments are also promoting these EVs because of their advantages like quite operation, zero pollution, less maintenance etc.

There are problems associated with electric vehicles such as non-availability of charging stations, run of only 60-80 km after full charging, long battery charging time (4-8 hrs. depending on battery size), low capacity of renewable sources of energy like solar energy, wind energy etc. which need to grow in the current scenario as 60% of the electricity is produced from the fossil fuel-based thermal power plants in India [2].

Fuel cell operated vehicles (FCVs) are the current development speeding up in research institutes and industries to overcome the problems associated with electrical vehicles. Fuel cell is a kind of device/cell which directly converts fuel into electricity purely with chemical reaction and no combustion process is involved for power production. Thus, no pollution is created in this like in IC engines. The fuel cell produces electrical energy which can be directly used to operate a DC/AC motor which further can be utilized to run a vehicle.

The utilization of solid oxide fuel cell (SOFC) in future power generation system is drawing critical consideration because of its advantages like high efficiency, fuel flexibility, and capacity to work without a costly catalyst, such as Platinum. To accomplish the full commercialization of SOFCs, researchers are exploring the possibilities of increasing their efficiency. Research on SOFC hybrid systems has improved the power generation effectiveness by consolidating a SOFC with an additional power generation unit. It has been shown that a hybrid system can be an incredible asset for increasing efficiency [3].

All are aware that the world is gradually moving towards the era of depleted fossil fuel resources and minimum air pollution. However, the literature indicates that still the nature has enough hydrocarbon fuel which can last for more than 30-40 years from now. Recent research shows that due to various limitations and several constraints on the adaptation of alternatives, around 90% of transport energy will continue to come from petroleum powered combustion engines [4,5].

2. Literature Review

2.1. Low Temperature Combustion Engines

Low Temperature Combustion Engines (LTCE) is an emerging Internal combustion engine technology that offers an attractive alternate to replace both spark ignition and compression ignition engines with some advantages like reduced emissions, low fuel consumption, wide variety of alternate fuels to use,

high efficiency, fast combustion, controlled combustion etc. These are divided into three types viz. premixed charged compression ignition (PCCI) engine, homogeneously charged compression ignition (HCCI) engine and reactivity control compression ignition (RCCI) engine [6][7].

2.1.1. Premixed Charged Compression Ignition

Premixed Charged Compression Ignition is a modern combustion process which is intended to be used in internal combustion engines and other types of motorized vehicles in future. A PCCI engine injects fuel and premixes the inlet charge during compression stroke. Thus premixed charge is too lean to ignite during the compression stroke; the charge will ignite only after the last fuel injection that ends near the top dead center (TDC). The fuel efficiency and working principle of a PCCI engine resembles with that of Diesel engine, but a PCCI engine can run with variety of fuels and also, the partially premixed charge burns clean. Due to the advantages like higher specific power output, higher fuel efficiency and low engine exhaust, it is a promising future engine technology [8].

Jeon J. and Bae C. [9] enumerate the use of dimethyl ether and hydrogen they found an increase in indicated mean effective pressure while decrease in CO, CO_2 and HC emissions with increased percentage of Hydrogen. They observed no change in NOx emissions.

Ibrahim et al. [10] state the use of Biogas with diesel fuel (Duel fuel) in predominantly premixed charge compression ignition and found increase in break thermal efficiency with increased biogas energy ratio. Emissions like NOx, CO, HC and smoke are found to be reduced.

Wang et al. [11] investigates the use of dimethyl ether gas-diesel fuel with LPG addition in duel fueled PCCI combustion. The results show a slight reduction in break thermal energy, PM and NOx emissions with increasing LPG.

Zehni et al. [12] experimentally use biodiesel and diesel fuel in PCCI combustion using CFD. The results show reduction in thermal efficiency, total HC, CO and NOx emissions up to 9.5%, 12%, 27% and 13% respectively. An increase in indicated specific fuel consumption by 6% is observed.

2.1.2. Homogeneous Charged Compression Ignition (HCCI)

An HCCI engine is a combination of both conventional Spark-Ignition engine (SI) and Compression Ignition engine (CI). The blending of these two engine designs offers diesel-like high efficiency without any difficulty and is inexpensive to deal with NOx and particulate matter emissions. In its most basic form, it simply means that fuel like gasoline or E85 is homogeneously (thoroughly and completely) mixed with air in the combustion chamber i.e. similar to a regular spark-ignited gasoline engine, but with a very high proportion of air to fuel i.e. lean mixture. As the engine's piston reaches the top dead center (TDC) on the compression stroke, the air-fuel mixture auto-ignites spontaneously and completely combusts without the spark plug assistance from compression heat, like a diesel engine. The result is the best of both engines i.e. low fuel usage and low emissions. The advantages of this engine are increased fuel efficiency, low emissions, clean & fast combustion and less frictional pumping loss [13].

Nathan et al. [14] experimentally use biogas as fuel in biogas-diesel HCCI combustion and the results show an increase in break thermal efficiency for higher inlet charge temperature and 50% biogas energy ratio. Reduction is observed in CO emissions. Reduction in NO emissions is less than 20 ppm. Smoke emission is less than 0.1 BSU whereas there is increase in HC emissions with increasing biogas energy ratio.

Bika et al. [15] use synthetic gas as fuel in HCCI combustion and find an increase in combustion efficiency with increasing H_2 composition and maximum combustion efficiency obtained is 88%. Increase in Peak in-cylinder temperature, in-cylinder pressure and peak heat release rate with increasing inlet air temperature is observed.

Lu et al. [16] state the use of gasoline and diesel blends as fuel in compound HCCI combustion engine. An increase in pressure and lower heat release rate with increasing premixed gasoline ratio is observed. Smoke, CO, HC and NOx emissions are reduced.

Yousefi et al. [17] investigate natural gas in HCCI with or without pre-chamber and find an increase in indicated mean effective pressure by 49.3%. In-cylinder pressure of 180 bar and heat release rate of

193.074 J/deg for modified chamber are observed. NOx emission is increased while CO and HC decreased for the modified chamber.

2.1.3. Reactivity Controlled Compression Ignition Engine (RCCI)

Reactivity controlled compression ignition (RCCI) engine is a combination of HCCI engine and PCCI engine. Reactivity controlled compression ignition is a form of low temperature combustion engine in which a low-reactivity fuel and air are well-mixed and compressed but the auto-ignition temperature of inlet fuel is not reached. During compression stroke a high-reactivity fuel is injected into the cylinder to form a localized mixture of low-reactive and high-reactive fuel. After injection, the whole fuel charge ignited at top dead center (TDC) by injection of a high-reactivity fuel. The RCCI combustion processes require two different fuels for its working. Low-reactivity fuel gets injected to the intake ports with a low pressure during the intake stroke. A High-reactivity fuel gets injected to the cylinder with the high pressure during and after compression stroke as conventional CI engine. Because of the compression ignition and lack of throttle control, RCCI resembles much like diesel engine process [7].

RCCI is a dual fuel engine combustion technology that was developed at the University of Wisconsin-Madison Engine Research Centre laboratories. RCCI is a variant of Homogeneous Charge Compression Ignition (HCCI) that provides more control over the combustion process and has the potential to dramatically lower fuel use and emissions. The advantages of this engine are low NOx and PM emissions, low heat transfer losses, high fuel efficiency, and no after-treatment systems requirement [18].

Paykani et al. [19] use natural gas as low reactivity fuel and diesel as high reactivity fuel in RCCI combustion. The results show reduction in NOx, smoke emissions, in-cylinder pressure and heat release with increased natural gas premixed ratio. While increase in CO and HC emissions with an increased natural gas premixed ratio is observed.

Park and Yoon [20] enumerate the use of gasoline and biogas as low reactivity fuel and diesel as high reactivity fuel in RCCI combustion and the results shows reductions in soot emissions and NOx emissions. Increase in CO, HC emissions and indicated specific fuel consumption is observed for biogas mode than gasoline mode.

Kalsi and Subramaniam [21] investigate hydrogen blended with CNG (HCNG) as low reactivity fuel and Pongamia pinnata biodiesel as high reactivity fuel in RCCI. The results show an increase in break thermal efficiency while emission like CO, HC, NOx and smoke are reduced.

Poorghas-emi et al. [22] experimentally use natural gas as low reactivity fuel and diesel as high reactivity fuel in numerical study of RCCI combustion. The result shows an increase of 5% gross indicated efficiency. Reduction in NOx emissions is observed while increase in CO and HC emissions has been controlled by increasing NG fraction.

The literature shows that RCCI engine produces very less emissions. HC and CO emissions present in the exhaust can be treated with the help of catalytic converter. When waste anode off gas of solid oxide fuel cell is used along with the petroleum fuel in RCCI engine, it produces additional power, consuming less petroleum fuel. Such RCCI engine setup requires only 10% of hydrocarbon/biodiesel fuel with 90% anode off gas as the remaining fuel, and produce less engine emissions.

2.2. Fuel cell

A fuel cell is an electrochemical device that directly converts a fuel to electricity by means of reactions on the surfaces of electrodes and transport of ions through an electrolyte. It can be thought of as a chemical battery whose reactants are fed from external sources rather than packaged as part of the battery. Fuel cells directly transform the chemical potential energy of a fuel into electricity, a high-value energy carrier that can be put to many uses. As a direct energy conversion device, fuel cells operate without an intermediate step of heat generation as seen in internal combustion and other heat engines.

The typical electrochemical reaction of hydrogen at the anode (Eq. (1)) and oxygen at the cathode (Eq. (2)) sides are shown below:

$$H_2 + O^{2-} \longrightarrow H_2O + 2e^- \quad (1)$$

$$½\ O_2 + 2e\text{-} \longrightarrow O^{2-} \quad (2)$$

$$H_2 + ½\ O_2 \longrightarrow H_2O \quad (3)$$

The fuel cells can be classified into two types mainly depending on their operating temperature. These are divided into low temperature fuel cells which operates at a temperature below 400° C and high temperature fuel cells which operates at a temperature above 400° C [23][24].

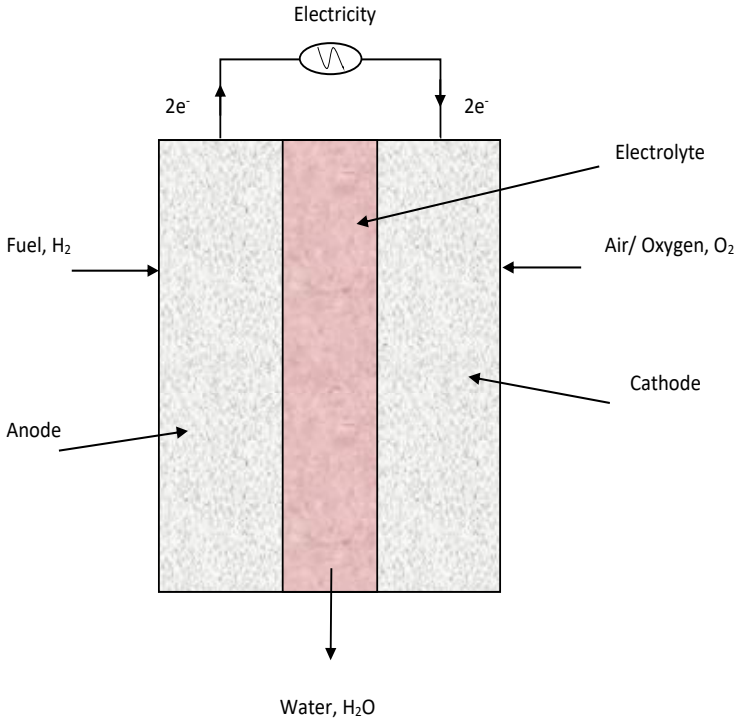

Figure 2.2. Schematic diagram of a fuel cell.

2.2.1 Low temperature fuel cells

Polymer Electrolyte Membrane Fuel Cell (PEMFC): These fuel cells are operating in the range from 80-180 °C temperature with commonly use perfluoro-sulfonic acid (Nafion) and acid doped PBI electrolyte. They generally have 60% electrical efficiency with direct H_2 fuel and 40% electrical efficiency with reformed fuel. Their typical fuel cell stack size is between 1 kW and 200 kW range.

They are mostly used for applications like backup power, portable power, distributed generation, transportation and special vehicles. These fuel cell have advantages like low operating temperature, quick start-up, reduced corrosion & electrolyte problem, environmentally friendly operation, fuel flexible, clean operation, cost-effective and less sensitivity to impurities. PEMFC generate power from Hydrogen which can be produced from a variety of sources including fuels like biomass, natural gas, renewables such as wind and solar power and nuclear energy from a few Watts to hundred kilo-Watts range [25].

Alkaline fuel cell (AFC): These fuel cells are operating at a temperature between 120°C and 250°C with commonly used aqueous potassium hydroxide soaked in a porous matrix or alkaline polymer membrane electrolyte. They have electrical efficiency of around 60%. Their typical fuel cell stack size is between 1 kW to 100 kW range. They are mostly used for applications like military, space, backup power, portable power and transportation. It has advantages like lower cost components, low operating temperature and quick start-up.

Zhang X. et al. [26] states that an alkaline fuel cell (AFC) produce low grade waste heat which can be effectively utilized by integrating a thermally regenerative electrochemical cycle (TREC) to make an AFC-TREC hybrid system. The results show that the maximum power output density of the proposed hybrid system is about 1.46~1.77 times the alone AFC when the regenerative efficiency of the TRECs is in 0.4~0.8 range. At 353 K operating temperature of AFC, maximum power output density is about 2 times for AFC-TREC hybrid system compared to AFC-TEG hybrid system, 2.42 times to AFC-refrigerator hybrid system, 1.17 times to AFC-heat driven hybrid system, respectively. So, the proposed model is more efficient to harvest the waste heat released from AFCs compared to any other AFC-based hybrid systems.

Phosphoric acid fuel cell (PAFC): These fuel cells are operating at a temperature of around 150 °C to 220 °C. These commonly use phosphoric acid soaked in a porous matrix or imbibed in a polymer membrane electrolyte. They have electrical efficiency of around 40%. Their typical fuel cell stack size

is around 10 kW to 400 kW range. They are mostly used for distributed generation. These fuel cells are suitable for CHP and increased tolerance to fuel impurities.

Wu M. et al. [27] enumerate that phosphoric acid fuel cell (PAFC) produces a large amount of waste heat along with electricity generation. This waste heat can be utilized to enhance the performance by integrating a thermoelectric cooler and a thermoelectric generator. The hybrid system is found feasible and effective and the numerical analysis show that the efficiency and power density of the proposed hybrid system increased by 2.8% and 2.3% respectively compared to the stand-alone PAFC. Low operating temperature, relatively low-cost electrolyte, high durability and established H_2-O_2 fuel cell technologies are some advantages of PAFC.

Bio-fuel cell (BFC): These fuel cells are operating at low temperature. They commonly use micro-organisms in Microbial fuel cell and enzymes in enzymatic fuel cell as electrolyte for their working. Their typical fuel cell stack size is of very less range and mostly used for portable electronics, biomedical instruments, environmental studies, military and space research. The advantages of these fuel cells are that they have cost advantage over other types of fuel cell. They do not use precious metal and produce energy from waste water treatment.

Palanisamy G. et al. [28] state about bio fuel cell (BFC)/microbial fuel cell (MiFC) and their uses. Microbial fuel cells have a great potential as an alternative energy conversion system for generating bioenergy. MFC involves microorganisms like Shewanella, Clostridium, Geobacter and Pseudomonas. The microbial fuel cells can be used for various applications like environmental-friendly energy production, electricity generation, wastewater treatment process, removal of organic material and nitrogen by wastewater treatment, phosphate recovery from wastewater, sulphide removal from wastewater, biosensor application and bio-hydrogen generation. The advantages of MFC are substrate is converted directly into energy by utilizing a biotic electro-catalyst, can operated at low or high temperature, any pH value and diverse biomass and generating a low amount of activated sludge from wastewater compared to the present conventional treatment technologies.

Direct methanol/ direct ethanol fuel cell (DMFC/DEFC): These fuel cells are operated at a

temperature of around 50°C to 140 °C. Commonly used electrolyte is the eutectoid mixture of Li2CO3 and K2CO3 in ratio of 62:38 for their working. Their typical stack size is around 100 W to 5 kW range. These are mostly used for notebook computers, mobile phones, military equipment's, golf carts, scooters, residential and small business establishments.

S.P.S. Badwal et al. [23] enumerate that direct ethanol fuel cell (DEFC) is varying in size from few watts to kW range. These fuel cells use ethanol as fuel which can be produced from a number of renewable biomass sources like sugarcane, corn, grass, wood and straw. The energy density compared to H_2 (which has 0.003 kW h/L) is 6.317 kW h/L for ethanol, 5.80 kW h/L for ethylene glycol and 4.8 kW h/L for methanol. The ethanol has 13 wt% hydrogen. DEFC is very attractive for a number of applications including transportation sector, portable power, backup and remote area power, distributed power and large-scale stationary power generation.

Micro fuel cell (MFC's): These fuel cells are the miniature form of either PEMFC/DMFC/SOFC. These have electrical efficiency of around 70%. Their typical stack size is of few Watts range and are mostly used for portable electronic devices and in place of batteries. Some advantages associated with these fuel cells are 100% fuel utilization, low cost technique, no humidification problem, ambient temperature operation and low catalyst loading.

O. Erdinc and M. Uzunoglu, [25] enumerate that on micro fuel cells (MFCs) lot of research has been done by reputed companies such as Samsung, Motorola, Toshiba, Sanyo, Panasonic and Sony which show that micro fuel cells can be used in mobile phones that can run for twice longer as compared to lithium battery with same size and can be recharged within 10 minutes. Similar study has been done on laptops and the result shows that laptops operating on FCs may work up to 5 h without refueling. The micro fuel cells can be used for applications like smoke detectors, security alarms, pagers, hearing aids, battery chargers, navigation systems and sensors.

2.2.2. High temperature fuel cells

Molten carbonate fuel cell (MCFC): These fuel cells are operate at a temperature of around 600 °C

to 700 °C and commonly use Molten lithium, sodium, and/or potassium carbonates, soaked in a porous matrix electrolyte for their working. They have electrical efficiency of around 50%. Their typical stack size is around 300 kW to 3 MW range and they are mostly used for distributed generation system and electrical utility. These fuel cells have high efficiency, suitable for CHP, fuel flexibility and hybrid-gas turbine cycle.

Zhang H. et al. [29] state that a MCFC can be integrated with an absorption refrigerator system as a bottoming cycle. This hybrid system is numerically analysed under different operating conditions like heat transfer coefficients, working fluid internal irreversibility inside the absorption refrigerator, some thermodynamic losses related parameters, and the operating current density, pressure and temperature of the MCFC. The result shows that maximum power density and the corresponding efficiency of the proposed hybrid system are increased by 3.2% and 3.8%, respectively in comparison to stand alone MCFC.

Direct carbon fuel cell (DCFC): These fuel cells operate between 600°C to 850°C temperature and commonly use granulated carbon power ranging from 10-1000 nm sizes electrolyte for their working. They have electrical efficiency of around 70%. Their typical stack size is around 1 kW to 2 MW range and mostly used for distributed generation system, auxiliary power and electrical utility. These fuel cells have high efficiency, produce pure CO_2 which can be stored & used commercially and can be used on low grade abundant fuel derived from coal, municipal and refinery waste product.

Zhang X. et al. [30] enumerate that a direct carbon fuel cell (DCFC) is coupled with a Thermo radiative device (TRD) to make a hybrid system. The waste heat can be harvested by using any of devices like thermo radiative device, thermophotovoltaics and thermoelectric converters. In this system the waste heat released from DCFC is used in a gallium antimonide thermo radiative device (TRD) to generate additional electricity. The simulation result exhibits a 1.48 times improvement and maximum power density 516 Wm^{-2} at the temperature of 972 K as compared to standalone direct carbon fuel cell hence hybrid systems overall performance can also be effectively enhanced by 48%.

Solid oxide fuel cell (SOFC): These are the fuel cells operating at a temperature of around 500 °C to

1000 °C which commonly use Yttria stabilized zirconia as electrolyte for their working. They have electrical efficiency of around 60%. Their typical stack size is around 1 kW to 2 MW range and are mostly used for distributed generation system, auxiliary power and electrical utility. These fuel cells are suitable for CHP, high efficiency, fuel flexibility, hybrid-gas turbine cycle and solid electrolyte.

Damo U.M. et al. [31] state that solid oxide fuel cell (SOFC) can be integrated with a microturbine to make a hybrid system. The result shows an increase in efficiency of the hybrid system which is around 35-40% in 250 kW to 1 MW range and 35-48% for a 5-10 MW SOFC-mGT system when an intercooler & reheater is used compared to conventional micro gas turbine. A total combined thermal and electrical efficiency of 85-90% can be reached. Along with increase in efficiency it also reduces harmful emissions to the environment.

Siemens Power Partnership and Mitsubishi heavy industry has built up a 220 kW-class pressurized SOFC–GT hybrid system which has worked for around 3000 hours with an efficiency of 53% [3] which shows that SOFC has the capacity ranging from low to high i.e. 1 kW to 2MW range and it is fit for high load applications [24]. In the present study the focus will be on generating additional power from the waste anode off gas of SOFC and not to use SOFC directly in automobile as a power producing unit.

2.3. Combined system involving Low temperature combustion engine and High temperature fuel cell

The concept of using a heat engine in an integrated cycle with a SOFC has been well known for many years. Theoretical and experimental studies of combined SOFC and heat engine cycles have started attracting many. Most of the studies mainly concentrate on the performance analysis of combined SOFC and gas turbine cycles. These studies include thermodynamics analysis, design and performance modelling of SOFC hybrid systems.

D. sanchez et al. [32], use hybrid system of conventional power plants with molten carbonate fuel cell. In this system CO_2 emitted by power plant is used as fuel in fuel cell. This hybrid system reduces the emissions and it has been estimated that there is around 10% increase in the rated efficiency of the stand-alone engine. The installation cost of the plant, power consumption by compressor is minimal which compensates for the higher specific emissions when compared to the chemical carbon capture.

X. zhang et al. [33], modeled high temperature fuel cell like SOFC and MCFC combined with different heat engines like Brayton, Otto, Diesel, Atkinson, Braysson, and Carnot engines to make a hybrid system. This hybrid system by utilizing the waste exhaust gas and heat from the high temperature FC is utilized in heat engine as input fuel is capable of attaining a high efficiency up to 70-90%. It also shows that endoreversible heat engines are more efficient then irreversible heat engines. Along with that emission are also greatly reduce for this hybrid system.

S.Ho Park et al. [34], reveal by thermodynamic study that waste anode off gas from SOFC can be utilized as fuel in HCCI engine with produces the additional power and shows a 7.8% and 0.9% efficiency improvement compared to simple SOFC system and SOFC-GT hybrid system, respectively. A significant emission reduction and levelized cost of electricity (LCOE) reduction has been noticed in SOFC-HCCI system in comparison to SOFC and SOFC-GT system.

Al-Rousan et al. [35] state that HHO gas can be produced from a fuel cell which can be used as fuel along with gasoline in an engine by varying the gap between the anode and cathode by 3, 5, 7 and 10 mm. The results show that maximum efficiency and maximum reduction of fuel can be obtained at 10 mm gap also HC and CO emissions can be reduced up to 40% at a gap of 5 mm.

Y. Duke. Lee et al. [36], compare three systems viz. simple SOFC, SOFC-GT hybrid system and SOFC-HCCI engine hybrid system which are used for electric power generation and it is found that SOFC-HCCI hybrid system shows higher electrical efficiency. The waste anode off gas from SOFC is used in HCCI engine for additional power generation and to reduce fuel consumption thus improving electrical efficiency of overall system. By economic analysis in cost of electricity 8.7% reduction estimated for SOFC-HCCI ($0.2792/kW) compared to SOFC ($0.3059/kWh).

H. Xu et al. [37], enumerate modeling study and compare DC-SOFC, DC-SOFC- regenerator and DC-SOFC- Otto heat engine. They found that Otto heat engine can effectively recover the waste heat from the DC-SOFC for additional power production especially at large operating current density. The results show that the equivalent power density of proposed system could be increased by up to 80% compared to the stand-alone DC-SOFC. The efficiency of the system is increased with increase in temperature and with decrease in the distance between electrodes.

W. choi et al. [3], present the first and the only experimental results of proposed hybrid SOFC-HCCI engine fueled anode off gas compared with SOFC-GT system and found that the proposed system is promising. This hybrid system is able to increase the efficiency, reduce the fuel consumption and engine emissions.

Thiyagarajan S et al. [38] enumerate that waste engine exhaust heat from CI engine is used in a thermoelectric generator to produce H_2 through reversible PEMFC, and this H_2 is inducted as fuel in the engine. In this hybrid system, 351 ml/min On-board H_2 can be produced in real time by using R-PEMFC. The results show an increase of 2.3% in power output with the use of H_2 as fuel. Also, at full load with H_2 induction HC, CO and smoke are reduced by 13.46%, 31.57%, and 24.7%, respectively but NOx emission is increased by 20% compared to diesel.

Matulic N et al. [39], state that proton exchange membrane fuel cell can be used to run auxiliary units like refrigeration unit, lights, cabin AC, radio unit etc. A big 7500 kg, 4-stroke diesel engine truck for 100% load is simulated. The total auxiliary unit load is estimated as 5 kW and for that a 120-cell stack with 0.6 V of PEMFC is used and the engine power is used only for driving the wheels. The results show that under actual road condition for 8 hour a day, 9% and 3L/100 km reduction in diesel fuel consumption. Total 9.6% reduction in CO_2 emissions.

Z. Wu. Et al. [40], state that a SOFC-HCCI engine hybrid system using waste anode off gas from fuel cell is used as inlet fuel in HCCI engine along with H_2 produced by metal hydride reactor using waste heat from engine for its working. It shows 58.75% of net electrical efficiency which is more than Reformer-PEMFC, SOFC, SOFC-CLHP and SOFC-GT systems. Studies also shows that by addition of H_2 with anode off gas, overall efficiency can be achieved as high as 79.54%.

F. D. F. Chuahy and S.L. Kokjohn [41], enumerate that SOFC-engine hybrid system is capable of achieving electrical efficiency of 70% (LHV) at a 1 MWe power level while producing minimal soot and NOx emissions. Final system efficiency calculations showed that both RCCI and HCCI operating modes have potential to be used as a hybrid system with high efficiency with minimum emissions.

The above studies show that a hybrid system consisting of a low temperature combustion engine and a high temperature fuel cell has the potential to be used in future as a system with high efficiency and low emissions. The studies also clearly reveal that most of the research is based on modeling and simulation and not much experimental work has been done. So, it is necessary to verify the hybrid system though experimental work.

3. Problem statement

The power and transport sector are mostly dependent on hydrocarbon fuels for their operation and studies indicated that there are various problems associated with these fuels. The major problems may be listed as follows:

i. Rising prices of hydrocarbon fuels over the years which continue to rise due to fuel scarcity.
ii. Emissions produced by burning hydrocarbon fuels are harmful for both living organisms and environment.
iii. Due to harmful emissions, problems like air pollution, global warming, smog, acid rain etc. increase.
iv. Most of the alternate fuels are not practically used due to non-availability, costly production technology etc.

Due to the above reasons it is necessary to go for alternatives of hydrocarbon fuel but complete diversion from it is very difficult as billions of vehicles are currently running on road which can’t be replaced at once. It might take another 20-30 years to adopt the alternatives. One is compelled to use the current technologies with suitable changes and modifications until the new technologies emerge effectively.

One of the effective solution in the current scenario may be to make a hybrid system utilizing the available engine technology and future fuel cell technology. This hybridization is likely to reduce the hydrocarbon fuel consumption to a great extent and increase the power production. This will ultimately reduce engine emissions, cost of fuel for same power generation and will also increase efficiency.

4. Scope of the work

The novelty of the proposed work is that untill now there is no experimental analysis done on low temperature combustion engines with anode off gas as fuel. In this work a reactivity-controlled compression ignition engine (RCCI) will be experimentally analyzed with anode off gas as fuel which is a waste gas obtained from solid oxide fuel cell (SOFC). The feasibility of actual system operation in various operating conditions will be studied. Modeling and simulation of low temperature combustion engine combined with high temperature fuel cell like SOFC-RCCI will be done and analyzed.

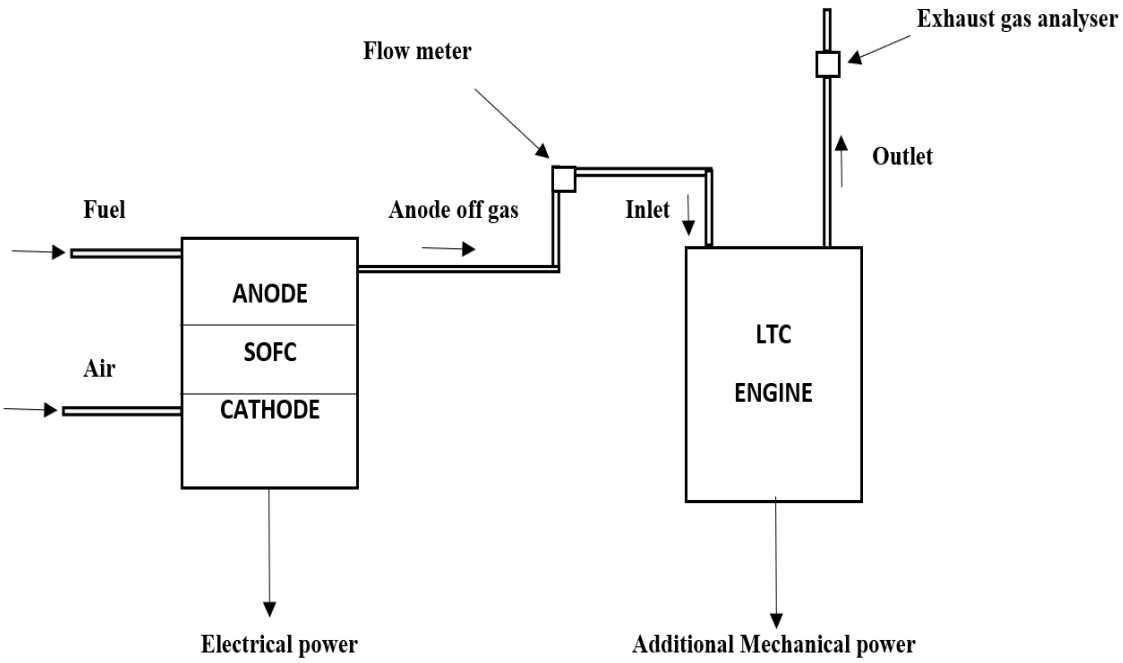

Figure 4.1 Working principle of LTCE-SOFC Hybrid system

There are many challenges which one would come across while working with the proposed RCCI engine setup. They may be summarized in two groups; (i) controlling parameters, structural factors, engine management (fuel ratio, injection strategies, EGR rate, compression ratio and bowl geometry); (ii) fuel management (chemical and physical properties of fuels that can affect the reactivity stratification in the cylinder). Most of these factors can be controlled but the main challenges that might affect the adaptability of RCCI engine and are needed to be taken care of are given below:

1. The control of the timing and magnitude of HRR for RCCI combustion, especially when attempting to operate at very high load.
2. Fuel impingement, consequently resulting in incomplete combustion due to early injection timing.
3. Possibility of knock in premixed combustion.
4. Need to develop control models on RCCI combustion to apply RCCI technique in commercial sense [42].

5. Methodology

The anode off gas will be directly used as fuel in RCCI engine consisting of constituents around 63.4% H_2O, 18.2% H_2, 3.3% CO, 15.1% CO_2 and air (contain O_2 and N_2). Total 78.5% diluent content present in anode off gas may be removed before feeding as fuel to the engine. Removal of H_2O may help in clean burning and increase efficiency of the engine.

The proposed experiment requires a number of components and arranging them in one unit is a challenging task. Keeping this in view it is proposed to procure H_2, CO & CO_2 gases in cylinders; integrate them with electric boiler, electric heater and static mixer as one unit and connecting with the RCCI Engine setup. The details are shown diagrammatically in section 5.1.

5.1. Emulation of anode off gas as intake fuel for RCCI engine

To accurately emulate the intake anode off gas for RCCI engine, some devices like mass flow controllers (MFCs), a water pump, an electric boiler, an electric heater and static mixer are used. First of all, water is fed into an electric boiler with the help of a water pump where it is converted into steam. After that air and CO_2 along with steam are fed to an electric heater where they are mixed with each other. The fuel components H_2 and CO are not put into the electric heater with O_2 to prevent an uncontrolled ignition in the intake system. Instead of that the gases H_2 and CO are mixed later using a static mixer [3].

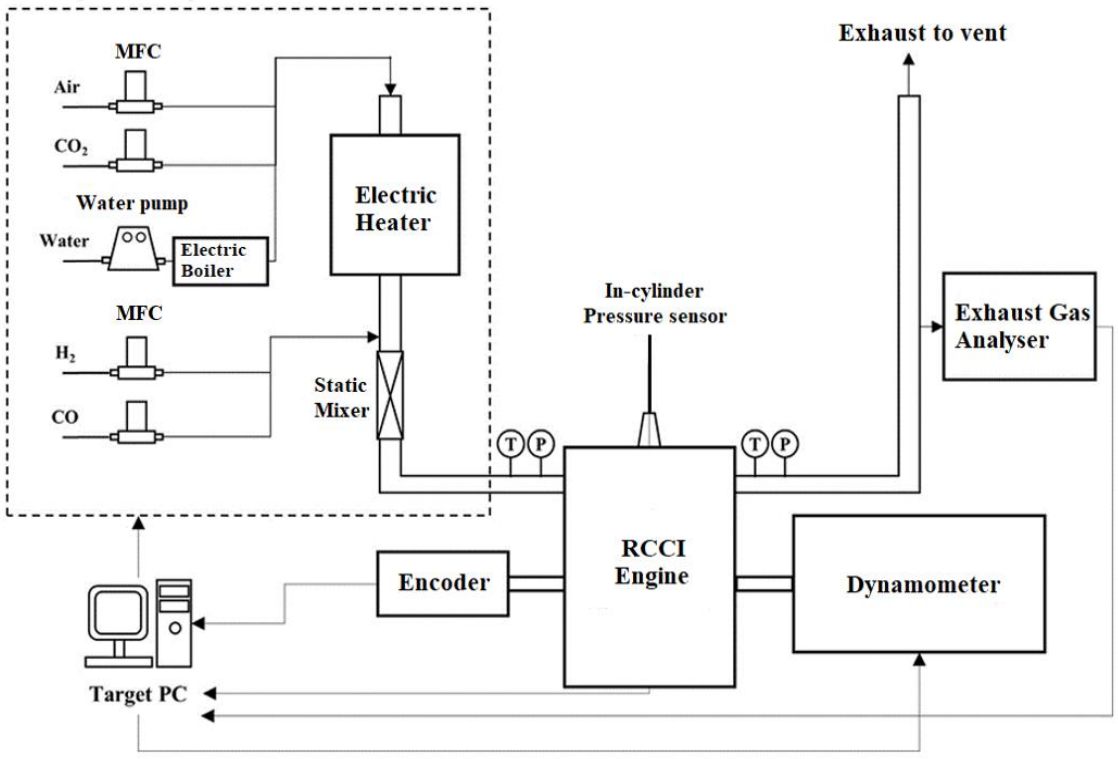

Fig 5.1. Experimental setup for emulation of anode off gas as fuel in RCCI engine.

6. Objectives:

Following are the proposed objectives of the research work to be carried out.

1. To develop an experimental setup of low temperature combustion engine and carryout analysis for performance parameters and exhaust emissions.
2. To model and simulate a low temperature combustion engine combined with high temperature fuel cell to propose a hybrid system.
3. To emulated solid oxide fuel cell (SOFC) anode off gas and use it as fuel for reactivity control compression ignition (RCCI) engine and to study the effect of varying parameters on the performance of combined system.
4. To validate the simulation results of the developed model with the results of real-life hybrid system.

The culmination of the proposed work is likely to produce a hybrid system with higher efficiency and reduced emissions utilizing waste gases of solid oxide fuel cell (SOFC).

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